Ability for In-Season Correction of Nitrogen Deficiency in Corn Using Chlorophyll Meters

Gary E. Varvel,* James S. Schepers, and Dennis D. Francis

ABSTRACT

Nitrate-nitrogen contamination of groundwater continues to be a major concern throughout the USA. These concerns are greatest in areas where groundwater is close to the soil surface and in areas that have irrigated crops with large N fertilizer requirements. Specific objectives of this work were to use the chlorophyll meter to determine in-season crop N status and to correct in-season N deficiencies in irrigated corn (*Zea mays* L.). Chlorophyll meter readings were used to calculate a sufficiency index [(as-needed treatment/well-fertilized treatment) × 100] and in-season N fertilizer applications were made when index values were below 95%. Using this procedure, maximum yields were attained if early season N levels were adequate to maintain sufficiency indexes between 90 and 100% at the V8 growth stage. However, if the sufficiency index at V8 was below 90%, maximum yields were not achieved with in-season N fertilizer applications because early season N was below that needed for optimum growth and yield potentials had already been reduced. Even in these cases, N applications did increase yields, but not to the maximum. These results did demonstrate that early N deficiencies could be corrected using chlorophyll meters and the sufficiency index approach when they were not severe. Although the objective was not tested in this study, less N fertilizer may be required when in-season monitoring is used as the basis for N application. Use of the chlorophyll meter and sufficiency index should also result in greater N use efficiency and less N being available for leaching to the groundwater since these applications are made when N uptake by corn is greatest.

In agricultural areas of the Northern Great Plains, NO_3–N contamination of groundwater is a major concern. These concerns are greatest in areas where groundwater levels are relatively close to the soil surface and where crops that require large N fertilizer inputs are grown. Corn is one such crop because it is often grown under monoculture systems on large areas of land in the central USA where groundwater levels are often relatively close to the surface.

Improving N management techniques is one approach to reduce the amount of N susceptible to leaching. Several methods for assessing and supplying crop N needs have been suggested and each has met with varying degrees of success. More recently, techniques that can be used during the growing season to make a rapid assessment of crop N status have been tested. One successful technique has been the use of chlorophyll meters for monitoring in-season N status. The technique has been successful because chlorophyll content is highly correlated with leaf N concentration (Wolfe et al., 1988; Lohry, 1989; Schepers et al., 1992).

Rapid and successful assessment of in-season N status of corn with the chlorophyll meter may allow for in-season correction of N deficiencies. One procedure proposed by Peterson et al. (1993) using chlorophyll meters appears to have promise, especially for irrigated corn where additional N fertilizer can be added using fertigation. But two questions arise regarding how these chlorophyll meter readings can be used. First, how and at what point does the chlorophyll meter indicate N is deficient? Second, once a determination has been made that the corn is N deficient, how late will in-season N applications be able to maximize yield?

A major study, with components designed to address the above questions, was prompted because of environmental concerns about NO_3–N contamination of groundwater in the Platte River Valley of Nebraska and other areas of the USA. The overall objective of the study was to investigate how best management practices can be used to reduce NO_3–N contamination of groundwater. Our specific objective was to evaluate use of the chlorophyll meter to determine in-season N status and to assess our ability to correct in-season N deficiencies when detected using the methods described above.

USDA-ARS and Dep. of Agronomy, Univ. of Nebraska, Lincoln, NE 68583. Joint contribution of USDA-ARS and the Nebr. Agric. Res. Div., Journal Series no. 11 687. Received 5 June 1996. *Corresponding author (gvarvel@unlinfo.unl.edu).

Published in Soil Sci. Soc. Am. J. 61:1233–1239 (1997).

MATERIALS AND METHODS

A study comparing irrigated monoculture corn and soybean [*Glycine max* (L.) Merr.]–corn cropping systems was initiated in 1991 on a uniform site in the Platte Valley near Shelton, NE, on a Hord silt loam (fine-silty, mixed, mesic Cumulic Haplustoll).

Prior to initiation of the study, the site had been in a monoculture corn production system for at least 10 yr. At the beginning of the study, corn stalks from the previous growing season were shredded and the entire area was disked twice before planting. Similarly, each following year, corn stalks from both cropping systems were shredded and the entire area, including that which had been in soybean, was disked twice before planting.

A split-split-split plot design was used with cropping systems as the main plots, corn hybrids as the subplots, and N fertilizer regimes as the sub-subplots with four replications. All phases of the monoculture corn and soybean–corn systems appeared each year starting with the 1991 growing season. Four commercially available Pioneer brand corn hybrids (3162, 3379, 3394, and 3417) differing in yield potential and maturity were selected for use in both the monoculture and rotation systems. All corn hybrids were planted between late April and mid-May in eight-row (91-cm row spacing) by 15.2-m-long plots at approximately 74 000 seeds ha^{-1}. Soybean in the soybean–corn rotation was planted in early to mid-May during the study using production practices typical to the area.

Nitrogen fertilizer as NH_4NO_3 was broadcast on the soil surface and immediately incorporated with a 6- to 7-mm irrigation in early June when corn was at approximately V1 growth stage (Ritchie et al., 1986). Six fertilizer N regimes including five fixed N fertilizer rates and one as-needed rate were used on both crops. Fixed rates of 0, 40, 80, 120, and 160 kg N ha^{-1} were used in 1991 and 1992 and 0, 50, 100, 150, and 200 kg N ha^{-1} for the 1993, 1994, and 1995 growing seasons. The N fertilizer rates were changed after the 1992 growing season

Table 1A. Mean squares and significance of rotation, hybrid, and N treatment effects in 1991.

Source	df	Chlorophyll meter readings						Grain yield
		V8†	V10	V12	V13	VT	R1	
		mean squares						
Block	3	674.5	147.2	322.2	50.2	76.0	23.5	25.6
Rotation (R)	1	6.0	4.8	4.1	0.1	0.0	1.5	8.9
Error *a*	3	17.2	6.9	3.3	3.3	1.9	6.5	1.6
Hybrid (H)	3	18.2	27.0	42.7**	51.2**	14.0**	18.2**	22.3**
R × H	3	4.6	7.8	9.7	3.5	0.7	2.3	1.4
Error *b*	18	18.8	13.4	8.1	3.9	1.0	2.3	3.6
N treatment (N)	5	44.0**	25.4**	9.2**	11.7**	8.5**	5.7**	0.8
Contrast‡	1	66.4**	51.0**	13.1**	24.7**	1.7	3.4	1.7
R × N	5	0.6	1.3	0.9	2.4	0.9	0.2	0.2
H × N	15	2.9	1.5	1.8	0.7	1.6	1.1	0.6
R × H × N	15	3.9	1.7	1.6	1.5	0.3	0.7	0.6
Error *c*	120	3.0	2.1	1.4	1.3	1.0	1.0	0.7
CV (%)		3.5	2.9	2.4	2.1	1.7	1.7	6.9

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Corn plant growth stages.
‡ Contrast (as-needed vs. 160 kg ha^{-1} N treatment).

because it appeared N rates used in 1992 did not maximize grain yields in the monoculture corn system. The as-needed N treatments were monitored and fertilized as described below. Irrigation was provided as needed with a linear drive sprinkler system.

In-season N status was monitored using SPAD 502 chlorophyll meters (Peterson et al., 1993) starting at the V8 growth stage and continuing through R2. Chlorophyll meter readings were taken from the uppermost mature leaf until the VT growth stage. After VT, meter readings were collected from the ear leaf. All measurements were taken on 30 randomly selected plants within each plot using the procedure described by Blackmer et al. (1993).

Chlorophyll meter readings from each sampling date were analyzed and readings from the as-needed treatment were divided by the maximum readings from the N fertilized treatments to obtain a sufficiency index, which is expressed as a percentage (Peterson et al., 1993). Additional fertilizer N (30 kg ha^{-1}) was applied by hand as a row application and watered in for the as-needed treatment within 24 h after chlorophyll meter readings had been taken if the sufficiency index was less than 95%. Based on this criterion, additional fertilizer was applied twice in 1991, three times in 1992, four times each in 1993 and 1995, and once in 1994. Usually, no additional fertilizer N was applied after corn reached the VT growth stage.

Analysis of 1992 results indicated we had an early season N deficiency in the as-needed treatments that we were unable to correct. These results indicated sufficient N must be present for early season growth from either residual soil N or fertilizer N application. To prevent this occurring in future years, 30 kg N ha^{-1} was applied by hand as a row application after emergence and watered in to all as-needed treatments in 1993 and 1994. The planter was equipped to supply starter fertilizer in 1995 and approximately 13 kg N and 18 kg P ha^{-1} was applied to all plots.

Soil samples were also taken just prior to planting on a yearly basis to a depth of 1.5 m from selected N treatments to determine residual N levels. The residual N levels for 1991 were determined from the entire plot area, while results from each of the other growing seasons were determined from samples taken from both as-needed and 0 kg ha^{-1} N treatments.

Final grain yield was determined with a plot combine by harvesting three of the center rows for the entire length of each plot. Yield data were adjusted to 155 g kg^{-1} moisture.

Data from the study were analyzed by year. All statistical analyses were performed using the Statistical Analysis System (SAS Institute, 1992).

RESULTS

No differences were obtained in residual N levels between as-needed and 0 kg ha^{-1} N treatments in any year. Residual N levels at the beginning of each growing season averaged across the as-needed and 0 kg ha^{-1} N treatments were as follows: (1991) 120 kg N ha^{-1}, (1992) 53 kg N ha^{-1}, (1993) 43 kg N ha^{-1}, (1994) 52 kg N ha^{-1},

Table 1B. Nitrogen treatment × rotation means for chlorophyll meter readings and grain yield in 1991.

N treatment	Chlorophyll meter readings						Grain yield
	V8	V10	V12	V13	VT	R1	
kg ha^{-1}							Mg ha^{-1}
			Monoculture corn				
0	46.6	49.4	48.8	53.6	56.2	56.1	11.2
40	48.3	49.9	49.5	54.2	57.0	56.6	11.6
80	48.4	49.8	49.6	54.9	57.3	56.6	11.5
120	49.0	50.8	49.9	54.7	56.9	56.7	11.7
160	50.0	51.4	50.8	55.0	57.6	57.4	11.9
As needed (60)	47.4	49.2	49.2	53.5	56.9	56.5	11.4
			Soybean–corn				
0	46.9	49.4	49.3	53.5	55.9	55.8	11.9
40	49.2	51.0	50.0	54.6	56.9	56.3	12.0
80	48.7	49.9	50.2	53.9	56.9	56.5	12.0
120	49.2	50.9	50.0	54.7	57.3	56.7	12.0
160	50.2	51.8	50.5	55.4	57.6	57.1	12.1
As needed (60)	47.7	49.5	49.7	54.0	57.1	56.4	11.8

Table 2A. Mean squares and significance of rotation, hybrid, and N treatment effects in 1992.

Source	df	Chlorophyll meter readings								Grain yield
		V8†	V9	V11	V12	VT	R1	R2	R3	
		mean squares								
Block	3	81.2	153.4	59.8	245.4	106.4	92.4	114.5	419.5	5.6
Rotation (R)	1	1001.5**	945.2**	619.9*	341.6*	323.4*	120.2	227.7	180.2	117.1**
Error *a*	3	1.8	7.5	38.7	26.3	19.9	15.6	44.6	28.1	0.6
Hybrid (H)	3	1.7	4.1	6.5	49.6**	43.4**	36.6*	72.9**	82.9**	5.4
R × H	3	4.3	6.2	1.7	3.4	5.3	0.5	5.5	3.7	5.1
Error *b*	18	12.8	8.4	9.1	8.0	7.7	10.2	15.1	15.1	3.0
N treatment (N)	5	100.0**	238.4**	250.7**	169.0**	256.4**	339.2**	422.5**	413.5**	18.4**
Contrast‡	1	259.0**	572.3**	636.4**	292.7**	308.8**	308.8**	389.0**	299.9**	18.9**
R × N	5	8.1	47.8**	39.7**	19.1**	41.9**	43.2**	56.7**	71.2**	4.1**
H × N	15	3.2	4.1	2.4	2.1	1.5	2.5	4.6	3.2	0.8
R × H × N	15	3.7	1.6	1.6	2.4	2.3	1.5	2.0	1.6	0.6
Error *c*	120	6.8	3.8	2.2	2.9	3.6	4.8	4.5	5.6	0.6
CV (%)		5.3	3.9	2.8	3.2	3.4	3.5	3.9	4.3	7.3

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Corn plant growth stages.
‡ Contrast (as-needed vs. 160 kg ha^{-1} N treatment).

and (1995) 50 kg N ha^{-1}. Residual soil N levels were considered to be very low in all years of the study except for 1991.

Chlorophyll meter readings taken at approximately V8 during each year of the study were used to determine initial sufficiency indexes for each hybrid in both rotations.

1991

No significant differences between crop rotation systems were obtained for chlorophyll meter readings at any of the sampling times (Table 1). Significant differences in chlorophyll meter readings were obtained between hybrids at late vegetative growth stages (approximately tasseling) and these continued throughout the rest of the sampling times. The initial set of readings taken at V8 indicated significant differences due to N fertilizer applications (Table 1). At this stage the sufficiency index was 95% for the as-needed treatment, which indicated a potential N deficiency, and fertilizer N (30 kg ha^{-1}) was applied to all as-needed treatments. Similarly, chlorophyll meter readings taken 1 wk later at V10 indicated the same results and an additional treatment of fertilizer N (30 kg ha^{-1}) was applied to all as-needed treatments. Chlorophyll meter readings from all successive sampling dates were significantly different between N fertilizer treatments, but their sufficiency indexes were above 95% so that no additional fertilizer N was applied.

Significant differences in grain yield were obtained between hybrids, but rotation and N fertilizer had no effect (Table 1). These results were not surprising because 120 kg N ha^{-1} was available at the beginning of the growing season and because ≈10 kg N ha^{-1} was applied on a weekly basis with the irrigation water for 8 to 9 wk starting at approximately V10.

1992

In contrast to results from 1991, chlorophyll meter readings for corn were significantly greater following soybean than in the monoculture corn cropping system during vegetative growth stages, but were similar during reproductive growth stages (Table 2). Significant differences between hybrids for chlorophyll meter readings were obtained at V12 and for each subsequent sampling time (Table 2). Again, N fertilizer significantly affected chlorophyll meter readings throughout the growing season (Table 2).

Initial readings taken at V8 indicated the sufficiency index for the as-needed treatment in monoculture corn

Table 2B. Nitrogen treatment × rotation means for chlorophyll meter readings and grain yield in 1992.

N treatment	Chlorophyll meter readings								Grain yield
	V8	V9	V11	V12	VT	R1	R2	R3	
kg ha^{-1}									Mg ha^{-1}
				Monoculture corn					
0	43.9	42.3	45.1	46.4	48.5	48.4	46.2	45.8	8.0
40	46.6	46.7	49.9	50.5	53.4	53.1	51.2	51.6	9.3
80	47.8	49.7	53.0	52.7	56.7	56.7	55.0	55.8	10.3
120	48.2	50.7	54.2	54.1	58.4	58.7	57.4	57.8	10.5
160	49.4	51.5	54.2	54.2	58.9	59.3	58.1	58.2	10.9
As needed (90)	44.1	43.3	46.7	50.0	54.3	55.9	54.7	55.4	9.9
				Soybean–corn					
0	49.3	49.6	51.9	51.9	55.1	53.1	51.6	52.0	10.7
40	51.3	51.2	53.8	53.9	57.3	56.6	55.8	55.9	11.3
80	52.0	53.1	55.3	54.9	58.8	58.7	57.5	57.8	11.9
120	52.3	52.8	55.6	55.7	59.1	59.3	59.0	58.9	11.8
160	52.6	53.6	55.7	55.5	59.7	59.5	59.2	58.3	11.7
As needed (0)	50.1	50.7	52.3	52.0	55.8	54.3	52.6	53.2	10.8

Table 3A. Mean squares and significance of rotation, hybrid, and N treatment effects in 1993.

Source	df	Chlorophyll meter readings V6†	V7	V8	V10	V13	VT	R1	R2	Grain yield
		mean squares								
Block	3	139.2	382.5	148.9	25.3	124.0	44.4	151.0	173.8	4.6
Rotation (R)	1	698.1*	1352.0**	1222.6**	1057.5**	988.3*	1133.9**	731.6*	710.7**	16.0*
Error *a*	3	42.0	36.8	44.0	20.2	79.9	14.4	27.9	8.9	0.8
Hybrid (H)	3	10.6	3.1	3.9	4.8	16.9	28.0**	62.9**	94.4**	28.6**
R × H	3	5.4	0.9	1.6	3.7	2.1	5.5	30.6**	31.9**	17.1**
Error *b*	18	9.1	6.2	6.2	4.8	5.9	5.2	5.3	5.4	0.7
N treatment (N)	5	69.8**	50.9**	360.6**	411.1**	536.4**	513.9**	947.4**	891.3**	44.7**
Contrast‡	1	8.8	15.2*	501.6**	476.3**	303.0**	105.7**	89.9*	45.6**	24.9**
R × N	5	44.3**	22.5**	73.6**	70.4**	75.8**	44.1**	47.4**	51.9**	20.4**
H × N	15	3.0	1.1	3.3	3.9	7.1	7.2	4.5	9.2*	2.1**
R × H × N	15	3.4	1.7	2.2	3.5	1.1	10.8	4.1	4.4	1.6
Error *c*	120	2.7	3.4	2.5	3.1	4.6	6.2	3.8	4.4	0.5
CV (%)		4.2	4.1	3.4	3.8	4.8	5.2	4.0	4.5	9.6

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Corn plant growth stages.
‡ Contrast (as-needed vs. 200 kg ha^{-1} N treatment).

was already showing a potential N deficiency. Based on these results, additional fertilizer N (30 kg ha^{-1}) was applied to as-needed treatments in monoculture corn on 29 June. Similarly, two more applications of fertilizer were applied to as-needed treatments in monoculture corn on 16 and 30 July, as chlorophyll meter readings continued to indicate a potential N deficiency for as-needed treatments based on the sufficiency index.

No additional fertilizer was added to as-needed treatments in the soybean–corn rotation because the sufficiency index remained at or above 95% until V12 and then decreased below 95% at later sampling times. Additional fertilizer was not added to these treatments at this time because N fertilizer management for yield is not effective after spikelet differentiation (Pearson and Jacobs, 1987).

Significant differences in grain yield were obtained between rotations and due to N fertilizer, but hybrids had no effect (Table 2). The rotation × N rate interaction was also significant for grain yield.

1993

Significant differences in chlorophyll meter readings were obtained between cropping systems and fertilizer rates throughout the growing season (Table 3). The rotation × N rate interaction was also significant throughout the growing season (Table 3). Similar to results from both previous years, significant hybrid effects did not occur until approximately tasseling.

Chlorophyll meter readings taken at V6 and V7 indicated significant differences due to N fertilizer applications (Table 3), but the sufficiency index for the as-needed treatments indicated adequate levels of N were available. However, readings taken at V8 indicated the sufficiency index had decreased rapidly for both rotation systems and was well below 95% and additional fertilizer N (30 kg ha^{-1}) was applied to all as-needed treatments on 2 July. Similar results were obtained for readings taken at 1-wk intervals for the next several weeks and additional treatments of fertilizer N (30 kg ha^{-1}) were applied to all as-needed treatments on 12, 22, and 30 July. No additional applications were made after 30 July.

Significant differences in grain yield were obtained between rotation, hybrids, and N fertilizer rates (Table 3). The rotation × hybrid, rotation × N rate, and hybrid × N rate interactions were also significant for grain yield.

1994

Significant differences in chlorophyll meter readings were obtained between cropping systems and fertilizer rates throughout the growing season (Table 4). The rotation × N rate interaction was also significant

Table 3B. Nitrogen treatment × rotation means for chlorophyll meter readings and grain yield in 1993.

N treatment	Chlorophyll meter readings V6	V7	V8	V10	V13	VT	R1	R2	Grain yield
kg ha^{-1}									Mg ha^{-1}
				Monoculture corn					
0	32.0	38.7	35.2	34.2	32.0	36.3	35.2	31.3	3.4
50	36.7	42.6	44.3	43.8	42.0	43.8	44.0	38.3	4.9
100	37.8	43.6	46.7	45.6	44.6	47.0	49.8	44.7	6.5
150	38.1	43.4	47.2	47.3	46.5	48.9	51.3	48.0	6.8
200	38.1	43.5	47.5	47.4	47.6	50.0	53.2	49.7	7.4
As needed (120)	39.5	43.5	42.8	42.1	42.3	47.6	49.2	48.7	7.3
				Soybean–corn					
0	40.0	46.8	46.2	44.7	42.6	44.8	42.9	40.5	6.0
50	41.7	48.6	49.6	48.5	46.6	50.1	50.2	47.9	6.4
100	41.1	48.0	50.9	49.5	48.4	52.3	52.3	50.2	6.5
150	40.7	48.7	50.6	50.0	48.9	52.8	53.6	51.1	6.4
200	40.9	48.3	50.8	50.2	49.8	53.1	55.0	52.5	6.3
As needed (120)	40.7	46.7	46.0	45.6	45.9	49.6	52.0	49.9	7.7

Table 4A. Mean squares and significance of rotation, hybrid, and N treatment effects in 1994.

Source	df	Chlorophyll meter readings V11†	V13	R1	R2	R3	Grain yield
		mean squares					
Block	3	26.4	206.7	2.6	150.7	192.4	14.2
Rotation (R)	1	108.8**	28.4*	110.7**	104.7**	79.2**	30.3**
Error *a*	3	4.1	1.2	1.4	0.5	3.8	24.2
Hybrid (H)	3	37.4**	12.4*	7.6*	14.9*	16.1	55.5**
R × H	3	3.3	2.2	2.7	1.3	0.0	2.1
Error *b*	18	3.5	3.0	1.8	4.3	7.5	2.8
N treatment (N)	5	42.4**	29.5**	53.9**	80.2**	113.4**	1.5*
Contrast‡	1	128.5**	57.9**	150.8**	108.6**	81.0**	0.0
R × N	5	7.7**	4.2**	7.9**	19.3**	31.4**	1.1
H × N	15	1.3	1.5	1.6	2.1	3.2	0.8
R × H × N	15	1.5	0.7	1.0	1.4	1.3	0.5
Error *c*	120	1.7	1.3	1.3	1.6	2.8	0.5
CV (%)		2.6	2.4	2.0	2.2	2.8	8.8

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Corn plant growth stages.
‡ Contrast (as-needed vs. 200 kg ha^{-1} N treatment).

throughout the growing season except at V13 (Table 4). In contrast to results from previous years, significant hybrid effects were obtained for all sampling times except the last one at late R3. Corn growth was severely delayed because of a hailstorm on 7 June and damage was different between hybrids, which probably contributed to some of the significant differences between hybrids early in the growing season.

The sufficiency index at V11 for the as-needed treatment indicated a potential N deficiency and additional fertilizer N (30 kg ha^{-1}) was applied to all as-needed treatments on 1 July. A severe windstorm during the following week caused major damage (stalk breakage) throughout the experiment and made it difficult to either obtain chlorophyll meter readings or use the data once it had been collected. No additional N was added to any of the as-needed treatments during the remainder of the growing season.

Significant differences in grain yield were obtained between rotations, hybrids, and N fertilizer rates (Table 4). The rotation × N rate interaction was also significant for grain yield.

1995

Significant differences in chlorophyll meter readings were obtained between cropping systems for the first

Table 4B. Nitrogen treatment × rotation means for chlorophyll meter readings and grain yield in 1994.

N treatment	Chlorophyll meter readings V11	V13	R1	R2	R3	Corn yield
kg ha^{-1}						Mg ha^{-1}
	Monoculture corn					
0	47.7	45.6	54.7	53.4	53.5	7.2
50	49.9	47.1	57.0	57.5	59.3	7.9
100	50.8	48.1	58.2	58.6	60.3	8.2
150	51.7	48.7	58.6	59.4	60.6	7.9
200	50.9	48.5	58.9	59.5	61.2	8.0
As needed (30)	48.1	46.1	55.4	56.3	59.3	8.0
	Soybean–corn					
0	50.6	47.1	57.8	57.5	58.7	8.5
50	51.8	47.7	58.4	59.4	59.7	8.5
100	51.9	48.7	59.6	59.7	61.4	8.5
150	51.9	48.6	59.1	59.5	61.0	8.8
200	51.8	48.8	59.5	59.3	60.9	8.9
As needed (30)	50.2	47.9	57.6	58.1	59.5	8.8

three sampling dates and for fertilizer rates throughout the growing season (Table 5). The rotation × N rate interaction was significant at the V8 to V9, V14, and VT sampling times (Table 5). Similar to results from all previous years except 1994, significant hybrid effects did not occur until approximately tasseling.

Sufficiency indexes for the as-needed treatments indicated a potential N deficiency for the first four samplings. Based on these results, additional fertilizer N (30 kg ha^{-1}) was applied to all as-needed treatments on 11, 18, and 25 July, and 1 August. Chlorophyll meter readings taken at R1 indicated the sufficiency index had increased to >95% and no additional N was applied to any as-needed treatments.

Significant differences in grain yield were obtained between rotation and N fertilizer rates (Table 5). The rotation × N rate interaction was again significant for grain yield.

DISCUSSION

Our objective was to determine if chlorophyll meters could be used to assess the N status of corn in as-needed treatments, which received either no preplant N or only a small amount at planting (starter). Crop N status was determined by comparing the chlorophyll meter readings from these as-needed treatments to those of our well-fertilized treatments. Corn in these as-needed treatments was determined to be N deficient if this comparison resulted in a sufficiency index of 95% or less, which according to Peterson et al. (1993) indicated a potential N deficiency. Using this procedure, we wanted to determine if in-season N applications could then be used to correct N deficiencies indicated for these as-needed treatments.

A necessary component of the sufficiency index procedure is that you must have a corn plot that has been fertilized for maximum yield. Chlorophyll meter and grain yield results from the N fertilizer treatments in the above study indicated we had sufficient N for maximum yield in all five growing seasons (Tables 1–5). Sufficiency indexes were calculated and N fertilizer (30 kg ha^{-1}) was applied to the as-needed treatments if they were 95% or below in all 5 yr. Based on this criterion, N fertilizer applications to as-needed treatments were

Table 5A. Mean squares and significance of rotation, hybrid, and N treatment effects in 1995.

Source	df	Chlorophyll meter readings V8†	V10	V12	VT	R1	R2	Grain yield
		mean squares						
Block	3	27.4	203.2	933.8	60.5	22.3	4.8	3.7
Rotation (R)	1	363.0**	176.5*	86.8*	86.3	0.3	0.7	69.5**
Error *a*	3	5.1	2.9	5.4	21.8	0.7	1.5	1.8
Hybrid (H)	3	1.7	13.4	15.8	151.5**	113.7**	101.8**	7.1
R × H	3	0.7	8.3	7.8	0.4	4.2	7.7	0.8
Error *b*	18	4.7	10.5	10.6	9.0	10.1	8.1	2.8
N treatment (N)	5	428.3**	405.9**	469.1**	253.4**	59.2**	112.5**	10.6**
Contrast‡	1	1383.9**	1324.7**	1192.4**	437.2**	84.4**	114.1**	9.6**
R × N	5	19.8**	17.9*	19.3**	9.0**	5.2	1.6	1.1*
H × N	15	2.7	2.7	3.0	2.1	2.4	1.3	0.3
R × H × N	15	3.3	4.0	2.7	1.3	1.4	1.6	0.5
Error *c*	120	3.5	6.4	3.2	1.8	2.6	1.7	0.4
CV (%)		3.5	5.0	3.6	2.4	2.9	2.3	6.2

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Corn plant growth stages.
‡ Contrast (as-needed vs. 200 kg ha^{-1} N treatment).

made as follows: two in 1991, three in 1992 to as-needed treatments in monoculture corn only, four in 1993, one in 1994, and four in 1995.

Grain yield results from as-needed treatments in all 5 yr indicated we were successful in attaining yields at or near maximum in three out of the five years (Tables 1–5). Grain yields from as-needed treatments in 1992 and 1995 were significantly lower than those from treatments with sufficient N for maximum yield (Tables 2 and 5). Those results were not something unique, but probably occurred because of a combination of factors in those years. In both 1992 and 1995, the initial sufficiency indexes for as-needed treatments were below 90%, which indicated they were severely N deficient. Nitrogen fertilizer applications were made immediately, but it appears yield levels had already been established. Initial N sufficiency indexes from the other 3 yr indicated none to only slight N deficiencies for as-needed treatments early in the growing season. When fertilizer applications were made in these years, yields were similar to those treatments that had sufficient levels of N applied earlier.

Several things became apparent as we examined the results from the various years. First, our results indicated that a severe N deficiency early in the growing season could be detected at the V8 growth stage using chlorophyll meter readings, but we were not able to correct that N deficiency and maximize yields. However, when the N deficiency is not as severe and sufficiency indexes were between 90 and 95%, we were able to use N fertilizer to correct the deficiency and maximum yields were attained. These results emphasize the importance of having sufficient N available for early season corn growth.

Residual N levels were sufficient for early season corn growth at the beginning of the study in 1991, but when the initial sufficiency indexes indicated a slight N deficiency, a couple of applications of fertilizer N to the as-needed treatments were made. No differences in grain yield were obtained between the as-needed and high N treatments (Table 1), probably because, as noted above, sufficient N was being supplied with the irrigation water to obtain maximum yield.

Using the same assumption that sufficient residual N was available for early season growth in 1992 caused problems. Apparently, residual N levels were not sufficient for early season corn growth and when the sufficiency index at the V8 growth stage indicated a severe N deficiency and N fertilizer applications were made, they were too late to correct that deficiency. Our approach after the 1992 growing season was to hand apply a small amount of N fertilizer at planting for as-needed

Table 5B. Nitrogen treatment × rotation means for chlorophyll meter readings and grain yield in 1995.

N treatment	Chlorophyll meter readings V8	V10	V12	VT	R1	R2	Grain yield
kg ha^{-1}							Mg ha^{-1}
			Monoculture corn				
0	46.6	44.3	42.5	48.8	53.6	52.6	8.6
50	52.6	49.5	49.4	54.2	55.9	55.9	10.3
100	54.4	51.8	51.1	56.1	57.3	57.0	10.5
150	55.8	53.2	52.9	57.1	57.3	58.0	10.6
200	56.1	51.9	53.1	56.8	56.6	57.5	10.5
As needed (120)	46.3	43.2	44.0	51.5	54.6	54.9	9.8
			Soybean–corn				
0	51.3	47.1	45.7	51.7	53.6	52.7	10.5
50	55.6	52.0	51.1	55.3	55.8	55.9	11.4
100	56.6	53.4	52.6	56.6	56.5	56.5	11.6
150	57.0	53.0	52.6	57.3	56.5	57.2	11.5
200	57.1	52.7	52.4	57.8	57.7	57.7	11.4
As needed (120)	50.8	47.2	46.8	53.8	55.6	55.3	11.0

treatments to supply enough N for early vegetative growth. Chlorophyll meter readings were then taken at the V8 growth stage and sufficiency indexes were used to determine if additional N fertilizer was needed. Using this approach, four additional applications of fertilizer N to the as-needed treatments in 1993 and one in 1994 maximized yields (Tables 3 and 4). In 1995 the planter was equipped to supply starter fertilizer and the additional N at planting was applied using that method. Apparently our starter application was insufficient for early season growth and by the time we measured sufficiency indexes, they were similar to those in 1992 and even with four applications of additional fertilizer N to the as-needed treatments we were unable to maximize yields.

Several things about using in-season N management for irrigated corn have been learned from this study. First, it was demonstrated that sufficient N must be available for early season corn growth because yield potentials appear to be set during this period, which is prior to the V8 growth stage when we started using the chlorophyll meter. If sufficient N was not available to sustain the corn to V8 (sufficiency index <90%), it was shown that the N deficiency could not be corrected with additional N applications. However, if the deficiency was not as severe (sufficiency index >90%), additional N applications were able to maximize yields.

Another thing learned was that chlorophyll meter readings were not significantly different between hybrids until tasseling or later except in 1994. Significant differences in chlorophyll meter readings between hybrids in 1994 occurred throughout the growing season, probably because of a severe hailstorm on 7 June. The corn survived, but the damage was not uniform, with some hybrids being affected more than others. These differences, manifested throughout the growing season, were detected by the chlorophyll meter. More importantly, even though we were able to detect differences between the hybrids, our results indicated these differences were not large and we could still use one sufficiency index for all the hybrids. For example, chlorophyll meter readings on the first sampling averaged 50.2, 51.1, 50.2, and 52.1 for 3162, 3379, 3394, and 3417, respectively. This meant we could successfully use the chlorophyll meter to monitor fields that may contain several hybrids at the early season growth stages when we still have time to make additional N fertilizer applications when N deficiencies are detected. It also indicates this could be done without having separate well-fertilized strips for each hybrid.

Overall, our results demonstrated that if sufficient N was available for early season growth, chlorophyll meter readings and the sufficiency index could be used to determine if additional N fertilizer was needed. Our results also demonstrated that maximum yields could be achieved when fertilizer applications were made based on chlorophyll meter readings and the sufficiency index if sufficient N for early season growth was available. Even in 1991, when it appears that our early season N fertilizer applications based on these criteria were not needed to maximize yields, the procedure worked. Additional N was needed, but in 1991, because of an extremely dry growing season, it was supplied by early and frequent applications of irrigation water that contained high NO_3–N concentrations. This is evidenced by the fact that grain yields for all N treatments were essentially equal, even though chlorophyll meter readings were significantly affected by N treatment throughout the growing season (Table 1). All the other growing seasons had precipitation amounts that were well above long-term averages and even though some irrigation was required, most of it occurred much later in the growing season. These irrigations did supply additional N, but all of them were supplied at a point in the growing season when they were not effective at increasing yields.

This study was not designed to determine how much N or how many N applications need to be made using this procedure, but comparison of the amounts of N applied at planting vs. the amounts applied in-season generally resulted in less N fertilizer being added when in-season monitoring was done. This application method should also result in less N being available for leaching to the groundwater since it is applied when N uptake by corn is greatest.

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